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A STUDY OF MARTIAN YELLOW CLOUDS THAT DISPLAY MOVEMENT

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ABSTRACT

Study of all reported instances of motion of Martian yellow clouds yields an analysis of their probable nature and properties. The yellow clouds seem to be initiated by wind-driven sand and tend to form in low latitudes. The limb and terminator projections seem to be quite different in nature, probably in part aqueous condensations. These occur primarily in middle latitudes.

1. INTRODUCTION

Among many observations of Martian "yellow clouds", that is, transient obscurations of portions of Mars' surface that can be observed visually or in photographs made through yellow filters, a few have occasionally displayed motion. As the only available direct indications of Martian atmospheric circulation patterns, these observations are of exceptional meteorological interest. Unfortunately, they are also exceedingly rare.

Yellow cloud motions have been observed either as displacements of obscurations located, roughly, in the central portion of the disk, or as displacements of limb or terminator projections. Hess [14] presented a streamline analysis of 18 Martian cloud motions based primarily on the extensive study of limb and terminator projections made by Douglass [8] during the apparitions of 1894 and 1896. De Vaucouleurs [6] has tabulated a half-dozen instances of yellow cloud displacements, including examples given earlier by Antoniadi [1]; and Slipher [24] has recently provided additional examples documented photographically.

In addition to the above, there exists a small but significant number of isolated reports of yellow cloud motion scattered through the literature. Furthermore, it is possible, in certain cases, to infer motions from reported yellow cloud observations for which the observer did not himself make this inference. The following is the report of an attempt to cull from the published literature all such reported instances of Martian yellow cloud motions, together with an analysis of their probable nature and properties.

2. SOURCES OF DATA

The first observer of Martian clouds was Maraldi, in 1704, according to Flammarion [10] who provided a comprehensive summary of all Martian observations up to the turn of the century. Schroeter, during the apparitions of 1787 and 1792, attributed apparent differences in the rotational period of Mars, as judged by the displacement of markings, to cloud motions. Later, P. Secchi suspected cloud motions as the cause of short-period changes in the appearance of Martian dark markings, and this was confirmed by Lockyer. To obtain quantitative information on yellow cloud motions it is necessary to turn to more recent sources.

In addition to the texts already mentioned, files of astronomical journals, observatory annual and periodic report series, and other pertinent literature sources have been consulted in search of instances of Martian yellow cloud motions. Attention has naturally been directed primarily to those sources richest in reports on Mars: for example, Lowell Observatory Annals [8]; reports of the Observatoires Jarry-Desloges [20]; reports of the Mars Section of the British Astronomical Association; reports of the Mars Commission of the French Astronomical Society; W. H. Pickering's [23] invaluable Monthly Reports on Mars; and, more recent, the Mars reports by the ALPO in *The Strolling Astronomer* [2]. In addition, many individual monographs, observatory reports, and published articles dealing with the subject of Martian clouds have been searched for reports of cloud motion.

3. OBSERVED MARTIAN YELLOW CLOUD MOTIONS

The results of this search for reported examples of Martian yellow cloud motions appear in tables 1 and 2. Table 1 includes reports of yellow clouds observed on the disk of Mars, as a result of their obscuration of surface details. Table 2 contains examples of cloud motions determined from observations of limb and terminator projections. The two groups have been separated because they are distinct from the observational standpoint; as will be seen below, they seem also to represent physically distinct phenomena on Mars. For clarity, in what follows the clouds of table 1 will be referred to as "yellow clouds" and those of table 2 as "projections". Of the latter group only one example, the cloud of October 20–27, 1924, overlaps Hess's collection and so the remainder of these examples, 35 in number, are all additional examples to the 18 he studied. The extreme rarity of such cloud motion observations is evident from the fact that over the period of 87 years spanned by the observations, only 53 examples of cloud motion are found. This means that their average frequency is little more than one per opposition period, although actual occurrences tend to be bunched around the perihelic oppositions, i.e. those of 1892, 1909, 1924, 1939, and 1956. It might be thought that this is an effect of more intensive scrutiny of Mars during these favorable apparitions; but, against this, no examples were found for the 1909 or 1939 oppositions, although adjacent years are in each case represented by cloud drift occurrences.

Two additional interesting phenomena involving the possibility of atmospheric motion should also be noted, although they are not cloud drifts, at least in the same sense as the examples given in tables 1 and 2. Dollfus [7] mentions a cloud, invisible to the naked eye but detectable by its polarization property, that drifted from Margaritifer Sinus and Mare Erythraeum to the Sabaeus Sinus-Hellespontus regions in several days, which he observed in May 1952. Also, Pettit and Richardson [22] mention the fact that the striking W-shaped blue cloud of June–July 1954 shifted in position, moving slightly to the southwest over a 30-day period, at a speed of 0.34 mi. hr.$^{-1}$ This phenomenon occurred between longitudes 60° and 120°.

4. RELIABILITY OF YELLOW CLOUD DRIFT ESTIMATIONS

Before attempting to interpret the cloud drift observations it is quite important to review certain aspects of their background so as to give some indication of their probable reliability. In the first place, all the cloud observations reported in tables 1 and 2 were made by experienced observers of the planet. However, the conditions of the observations differ considerably; and, particularly, they have been interpreted as cloud drifts in various ways, which should be clearly understood at the outset.

Some of the cloud observations have been interpreted as cloud motions by the observer himself, whereas others have been so identified by the present writer. An indication of this is given in the tables. Naturally, instances of cloud motion described by the original observer must be given more credence. Cloud drifts are ordinarily detected by noting displacements that occur on successive nights, although it seems sometimes to be possible to estimate motion during the course of a single night's observing. Naturally the question of whether one is really viewing the same cloud in a displaced position, or a different cloud arises; the original observer can best answer this question.

On the other hand many of the limb and terminator projections reported, for example, by the Observatories Jarry-Desloges to have occurred on successive nights seem fairly certain to be genuine cases of cloud motion and I have so interpreted them. If a significant projection was noted, and one night later another was reported in a nearby location, the displacement has been attributed to cloud motion. This procedure clearly involves the exercise of subjective judgment about what cloud drifts are physically possible.

TABLE 1.—*List of Martian yellow clouds that displayed motion*

A	B	C	D	E	F	G
1873 24–25 May	11–12 Feb.	15/15	315/305	Aeria	W/16	[1]
1905 27–29 July*	15–16 Mar.	11/20	210/215	Cerberus-I to Elysium	SSE/4	[15]
1907 29–30 July	20–21 Apr.	0/−20	270/220	Libya to M. Cimmerium	WNW/12	[6]
1911 11–18 Oct	2–7 Aug	0/−40	270/210	Libya to Eridania	NW/13	[6]
1911 13–14 Nov	21–22 Aug	−70/−70	335/315	Hellas	W/20	[1]
1922 9–12 July	29–31 Mar	0/30	30/40	Margaritifer S. to Chryse	SE/9	[6]
1924 9–10 Aug	14–15 May	15/0	280/290	Isidis R. to Libya	NNE/22	[24]
1926 25–26 Oct	31 July–1 Aug	10/−30	270/255	Libya-Isidis to Ausonia	NNW/55	[6]
1937 25–29 May	22–24 Feb.	10/25	80/60	Candor to Niliacus L.	SW/8	[6]
1941 12–28 Nov	31 July–10 Aug	30/−40	270/140	Libya to Phaethontis	NW/10	[6]
1943 3–5 Oct	3–4 Aug	0/−20	270/240	Libya to Hesperia	NW/25	[24]
1954 2 June	13 Mar.	−5/−10	115/108	Ulysses to Phoenicia L.	NNW/—	[2]
1956 22–25 Aug	29–31 May	−42/−38	20/350	Argyre to Noachis	WSW/15	[13]
1956 28 Aug.–4 Sept	2–6 June	−38/10	350/290	Noachis to Syrtis Major	SW/18	[13]
1958 12–15 Oct	29–31 July	20/−25	265/230	Isidis R. to Hesperia	NW/24	[24]
1961 19–21 Jan	13–14 Oct	40/40	260/230	Casius to Elysium	W/20	[19]

A Terrestrial date of observation.
B Equivalent Martian Southern Hemisphere date.
C Beginning and ending latitude (minus indicates Southern Hemisphere).
D Beginning and ending longitude.
E Region on Mars.
F Direction from which motion occurred/average speed, m.p.h.; estimates are mostly by the writer, based on reported cloud positions, except where average direction and speed were given in the reference.
G Reference.
*Identified as a case of cloud motion by the present writer.

TABLE 2.—*List of Martian projection clouds that displayed motion*

A	B	C	D	E	F	G
1890—5-6 July	21-22 Mar	40/40	52/41	Tempe	W/13	[4]
1892—2-3 July	12-13 Apr	−50/−50	335/326	Hellespontus	W/18	[5]
1892—11-13 July	19-20 Apr	−47/−46	344/357	Noachis	E/7	[5]
1894—25-26 Nov	10 Aug	−32/−23	44/49	Protei	SE/13	[9]
1900—7-8 Dec	24-25 Oct	−4/−1	336/322	Sabaeus to Icarium	WSW/27	[16]
1903—26-27 May	23-24 Jan	18/26	40/32	Chryse	SW/15	[16]
1911—6-7 Oct.*	18-19 Aug	−45/−40	295/255	Hellas to Ausonia	W/77	[20]
1912—15-16 Jan.*	23-24 Sept	−40/−45	340/300	Noachis to Hellas	W/48	[20]
1913—31 Dec./1 Jan.*	7-8 Oct	−45/−45	65/50	Argyre	W/16	[20]
1914—25-26 Jan.*	20-21 Oct	−45/−45	10/25	Argyre	E/14	[20]
1914 28-29 Jan.*	21-22 Oct	−45/−45	347/356	Argyre	E/10	[20]
1914—2-3 Feb.*	23 Oct	−15/−15	333/318	Deucalionis R	W/38	[20]
1914—6-7 Feb.*†	25 Oct	−10/−40	345/10	Sabaeus S. to Argyre	NE/55	[20]
1914—10-11 Feb.*	27 Oct	−45/−45	260/193	Hellas to Eridania	W/85	[20]
1914—17-18 Feb.*†	30-31 Oct	−42/−42	155/150	Phaethontis	W/5	[20]
1915—24-25 Jan.*†	20 Oct	−45/−40	165/135	Phaethontis to Icaria	W/33	[20]
1915—28-29 Dec.*	27-28 Oct	−10/10	210/190	Aeolis to Elysium	SE/30	[20]
1924—10-13 Oct	25-26 June	−44/−32	313/319	Yaonis to Hellas	S/5	[1]
1924—20-27 Oct	30 June-5 July	−40/−40	287/236	Hellas	W/8	[23]
1937—2-5 May	10-12 Feb	10/10	285/270	Syrtis Major to Isidis	W/6	[6]

A Terrestrial date of observation.
B Equivalent Martian Southern Hemisphere date.
C Beginning and ending latitude (minus indicates Southern Hemisphere).
D Beginning and ending longitude.
E Region on Mars.
F Direction from which motion occurred/average speed, m.p.h.; estimates are mostly by the writer, based on reported cloud positions, except where average direction and speed were given in the reference.
G Reference.
*Identified as a case of cloud motion by the present writer.
†Judged by the writer a doubtful cloud motion case because of limitations of the observed data.

The Jarry-Desloges observers noted the position of projections only approximately, by general references to surface markings, and as a result it is doubtful whether the inferred drift directions are reliable to within less than $\pm 15°$ or the speeds to ± 40 or 50 percent. The remainder of the drifts reported in tables 1 and 2 can probably be assigned, to be conservative, a reliability of perhaps $\pm 10°$ in direction and ± 25 percent in speed, although these estimates are quite subjective. Drifts are in all cases averages, computed from the initial and final reported cloud positions, without regard to such interesting day-to-day variations as have occasionally been reported, for example, by de Vaucouleurs [6]. Most cloud positions are reported in terms of Martian surface markings; and, in the absence of other indications (such as an accompanying sketch, or a detailed description), clouds have been assumed to be located at the latitude and longitude of the approximate center of the reported area or marking, as determined by reference to the maps given by Slipher [24], de Vaucouleurs [6], and Antoniadi [1]. Most of the tabulated latitudes and longitudes have been rounded off to the nearest 5° so as to reflect the probable accuracy involved, although in a few cases the available information has warranted a more precise position indication.

The Martian dates are computed, following custom, according to an equivalent Martian calendar whose southern hemisphere vernal equinox occurs on March 20. In practice this date is found by determining, from an ephemeris for the observation date, the longitude of the sun as seen from Mars (the planetocentric longitude of the sun), adding or subtracting 180°, and finding the nearest terrestrial date having an equal solar longitude; this is the equivalent Martian southern hemisphere date.

5. COMPOSITION OF MARTIAN YELLOW CLOUDS*

Mars' surface consists of large dark areas, the "maria", superimposed on an even more extensive bright colored background, which is usually referred to as "desert". In fact the available evidence, chiefly Dollfus' [7] polarization studies, indicates that these desert areas are composed of finely divided mineral material, possibly limonite. The occasional obscuration of surface details by what must be dust storms, and the general lack of moisture on the planet, also support the desert hypothesis.

Taking all the evidence, both direct and indirect, into account, it is reasonable to suppose that the Martian deserts are in fact broad expanses of finely divided mineral material that might as well be called sand (although its composition may differ from the terrestrial variety). This Martian sand must have been produced by various weathering processes, just as is the terrestrial kind, except that the action of flowing water has not been involved to any extent, at least recently. Without attempting to speculate about the details, it seems also fair to assume that these weathering processes should produce a range of sizes of sand grains. According to Bagnold [3], individual grains of sand lying on the ground are acted upon by two forces. The wind blowing over them exerts a drag force which is proportional to the cross-sectional area of the grain, and to the square of the "friction velocity", v_*, which is a characteristic velocity associated with the turbulent air flow, of the form

$$\beta \rho v_*^2 d^2;$$

ρ is air density, d is the particle diameter, and β is some constant. The tendency of this air drag force to tumble the grains is opposed by a vertical force, the resultant of gravitation and buoyancy, equal to

*Conclusions similar in many respects to results of this section were also reached (independently) in the very interesting study by J. A. Ryan "Notes on the Martian Yellow Clouds, Part I (Preliminary Copy)", Engineering Paper No. 1990, Douglas Aircraft Co., Santa Monica, Calif., 1964, 24 pp. (mimeo.)

$$\frac{\pi}{6} d^3(\sigma-\rho)g,$$

where g is the gravitational acceleration and σ is sand density. When the moments associated with these forces are just equal, a threshold value of v_* is defined that is just sufficient to cause sand grains of diameter d to move. Equating the moments, it develops that

$$v_*=A\left[\left(\frac{\sigma-\rho}{\rho}\right)gd\right]^{1/2} \tag{1}$$

where A, a constant, involves in addition to constants already introduced, the (approximately constant) angle between the vertical and the line joining adjacent grain centers, because the moments depend on this angle.

Now it is known from careful experimentation that the phenomenon of turbulent drag on sand grains is associated with a threshold value of the Reynolds number, Re, equal to about 3.5. For smaller values, vortex shedding stops and the flow around individual grains is laminar. Thus we can also write

$$Re=v_*d/\nu=3.5, \tag{2}$$

where ν is the air's kinematic viscosity. Combining equations (1) and (2) we find a threshold sand grain diameter, d_*, the smallest for which movement occurs:

$$d_*=\left(\frac{3.5}{A}\mu\right)^{2/3}(\sigma\rho g)^{-1/3}, \tag{3}$$

ρ being negligible compared with σ.

The dynamic viscosity, $\mu=\rho\nu$, depends only slightly on pressure and temperature and so it follows, using subscripts M for Mars and E for Earth, that, very closely,

$$\frac{d_{*M}}{d_{*E}}=\left(\frac{\rho_E g_E}{\rho_M g_M}\right) \tag{4}$$

Martian gravitation is about 40 percent of Earth's; the exact value of the Martian surface pressure is at the moment subject to some debate, but it probably lies between 1 and 10 percent of Earth's. Consequently we find from equation (4) that the critical diameter for sand motion on Mars is between 3 and 7 times larger than on Earth.

From equation (1) it also follows that

$$\frac{v_{*M}}{v_{*E}}=\left(\frac{\rho_E g_M d_M}{\rho_M g_E d_E}\right)^{1/2} \tag{5}$$

from which it can be concluded that the critical friction velocity for sand movement on Mars is between approximately 3 and 15 times that on Earth.

At the Earth's surface the threshold diameter for sand grain motion is about 0.1 mm., corresponding to a value of v_* of about 15 cm. sec.$^{-1}$ The corresponding wind speed for sand motion, $\bar{u}(z)$, is given by Prandtl's well known logarithmic velocity profile law,

$$\bar{u}(z)=\frac{v_*}{k}\ln(z/z_o) \tag{6}$$

where z is height above ground, z_o is a measure of the surface roughness, and $k=0.4$ is von Karman's universal constant. This will amount to winds of 1 or 2 m. sec.$^{-1}$ at heights of a meter. For higher wind speeds, larger sand grains begin to move, up to an ultimate value determined by the size of the largest grains present. Sand grains become airborne and progress downwind in bouncing trajectories, a process known as "saltation". As descending grains hit and rebound, sometimes dislodging others, more and more sand grains become involved in the motion up to a fixed quantity, governed by the capacity of the sand to absorb momentum from the air. This amount naturally depends on wind speed, and the quantity of sand driven by a given wind can be calculated.

It seems likely that the yellow clouds of table 1, which obscure the surface features of Mars, are initiated by the process just described. The wind speeds required to initiate sand motion on Mars, even if according to equation (5) they are considerably greater than on Earth, are comparable with the drift velocities of the yellow clouds of table 1, which average 18 mi. hr.$^{-1}$ (8 m. sec.$^{-1}$). To show this we conclude first, from equation (6) that

$$\frac{\bar{u}_M}{\bar{u}_E}=\frac{v_{*M}}{v_{*E}}\frac{\ln(z/z_{oM})}{\ln(z/z_{oE})} \tag{7}$$

Over a desert the roughness length, z_o, is a measure of the size of the sand grains that make up the desert surface. On Earth a representative value of the roughness length over a level desert is 0.03 cm., according to Pasquill [21]. By equation (4) we might estimate that on Mars a corresponding value would be 0.3 cm. Assuming further that the driving sand motion takes place very near the surface, at or below about $z=1$ m., (this is what happens on Earth) we find that

$$\frac{v_{*M}}{v_{*E}}=1.4\left.\frac{\bar{u}_M}{\bar{u}_E}\right]_{z=1\text{m.}} \tag{8}$$

Thus, corresponding to ratios of v_{*M}/v_{*E} of 3 to 15, we find that $\bar{u}_M/\bar{u}_E$ equals about 2 to 10. The critical values of $\bar{u}$ for sand motion on Earth being about 1 or 2 m. sec.$^{-1}$ at $z=1$ m., the observed average Martian yellow cloud drift of 8 to 10 m. sec.$^{-1}$ could certainly correspond to the velocity of low-level, wind-driven sand.

The initiation of sand motion within a few meters of the Martian surface involves particles having diameters somewhat larger than on Earth, perhaps 0.5 to 1 mm., according to equation (4). This will be accompanied, of course, by the raising of finer grains of dust to much greater elevations. Dust will remain suspended in an atmosphere for long periods when its settling speed is smaller than the vertical wind fluctuations due to turbulence. The actual numerical values suggested in the above analysis are somewhat tentative, but there appears to be little reason to suspect the general nature of the results apart from the possibility of minor adjustments. Thus we can formulate a picture of the Martian yellow clouds as being composed of wind-driven sand grains moving by saltation within a few meters of the Martian surface, accompanied by an overlying dust cloud, of much smaller particles, extending, perhaps, to many thousands of meters. The composition of the Martian limb and terminator projections of table 2 must be much different from this. It seems probable that these clouds are, in part, aqueous condensations. Since they are reported to extend to very great elevations, over 50 km. at times, and have on occasion been observed as completely detached from the Martian surface, they are evidently quite different in nature from the low-lying yellow clouds.

6. LOCATION OF MOVING CLOUDS

In table 3 the frequency of origin of the moving clouds is presented as a function of surface temperature at the location of their origin, as determined from tables 1 and 2, and the temperature values presented by Gifford [12]. There seems to be a preference for the low-level yellow clouds to originate in regions of higher surface temperature than do the projections. This is consistent with the hypothesis that the former are desert sand and dust storms. On the other hand it is also true that the warm regions are in general the ones most easily observed from the earth. In table 4, the frequency of occurrence of the moving cloud origins is given as a function of latitude; and in table 5 the same information for the terminal position of the moving clouds appears. These tabulations indicate clearly that the projections are mid-latitude phenomena, whereas the yellow clouds are primarily found in lower Martian latitudes.

Summarizing these positional aspects, we can conclude that the moving yellow clouds tend to form in low latitudes, near the thermal equator. The projections, on the other hand, occur primarily in the middle latitudes and their motion does not show any clear latitudinal component.

TABLE 3.—*Frequency of average seasonal surface temperature of the place of origin of moving clouds*

Temperature (°K.)	Yellow clouds (percent)	Projections (percent)
240°–249°	6	10
250°–259°		30
260°–269°	12	10
270°–279°		40
280°–289°	37	10
290°–299°	44	
	(16 cases)	(20 cases)

TABLE 4.—*Moving cloud frequency as a function of latitude of position first observed*

Original latitude (N or S)	Yellow clouds (percent)	Projections (percent)
>60°	6	
50°–59°		5
40°–49°	6	65
30°–39°	19	5
20°–29°	6	
10°–19°	31	25
0°– 9°	31	
	(16 cases)	(20 cases)

TABLE 5.—*Moving cloud frequency as a function of latitude of final position*

Final latitude (N or S)	Yellow clouds (percent)	Projections (percent)
>60°	6	5
50°–59°		5
40°–49°	12	50
30°–39°	25	10
20°–29°	31	10
10°–19°	19	15
0°– 9°	6	5
	(16 cases)	(20 cases)

7. MOVING CLOUDS AND MARTIAN CIRCULATION PATTERNS

Hess [14] showed a possible streamline map of Mars based on cloud movements determined from projection observations, for the southern hemisphere summer. The projection data of table 2 extend the observational material to all other Martian seasons, but there are too few cases in each season to permit an attempt to draw maps similar to Hess's.

The yellow cloud motions of table 1 exhibit a tendency that may well be related to a Martian circulation pattern; namely they tend, generally speaking, to drift equatorword, or at least toward the position of the thermal equator. If the yellow clouds are analogous to terrestrial cyclonic storms, this behavior presents a curious problem since terrestrial low-latitude cyclones tend to move poleward. Two possible alternative explanations have suggested themselves. Perhaps the yellow clouds are associated with polar outbreaks, similar to "northers". This would explain their direction of motion within the framework of a terrestrial analogy. On the other hand the following ideas may apply.

While this report was being written, the important Mars studies by Miyamoto [18] were received. In these he identifies four drifts observed since 1956. One is a yellow cloud that appeared over the Neith-Casius regions, moving to Elysium, around December 10, 1962 (planetocentric solar longitude equals 21°), which exhibited a drift from the west quite like that of the 1961 example of table 1. A second yellow cloud drift is reported as having occurred between January 29 and February 7, 1963, from Noachis and Sabaeus Sinus across the equator to the Aeria-Neith regions, from a southwesterly direction.

At approximately this time a large, persistent, bright cloud appeared over the Tempe-Arcadia-Proportis regions.

This complex formation developed from the east according to Miyamoto, as judged by its position at the successive appearances of these longitudes until April. The fourth cloud is the well known great storm of 1956. The general development, during August to September 1956, of this tremendous, planet-wide disturbance has also been widely interpreted as progressing from east to west, although in table 1 the present writer has indicated that individual yellow clouds or storms forming part of this development moved from the west, following the argument by Heintz [13], who based his conclusions as nearly as possible on day-to-day observations. There may in fact be no great inconsistency between these viewpoints. The motions of individual storm systems lasting for a few days need not necessarily be the same as the general development of a hemispheric disturbance that persists for over a month, even though the two may be dynamically related.

Miyamoto has suggested that such storms as these two great disturbances may be related to the breakdown of a symmetric regime of the general circulation of Mars into a wave regime, as predicted theoretically by Mintz [17]. Gifford [11] pointed out that the yellow clouds, such as those documented in table 1, are generally speaking too small to be related to large-scale baroclinic wave instability. Their generally equatorward drift may imply that they are steered by the tropical portion of a symmetric general circulation cell. On the other hand both the 1956 storm and the great Tempe-Arcadia development of 1963 are large enough to correspond to the dominant wave number on Mars, which was calculated by Mintz to equal 3.

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REFERENCES

1. E. M. Antoniadi, *La planète Mars, 1659–1929*, Hermann et Cie., Paris, 1930, 239 pp.
2. D. P. Avigliano, "Mars, 1954," *The Strolling Astronomer*, vol. 8, Nos. 9–10, Sept.–Oct. 1954, p. 109.
3. R. A. Bagnold, *The Physics of Blown Sand and Desert Dunes*, Methuen, London, 1954, 265 pp.
4. W. W. Campbell, "Notices of the Lick Observatory," *Publications, Astronomical Society of the Pacific*, vol. 2, No. 10, 1890, pp. 248–249.
5. W. W. Campbell, "Notices of the Lick Observatory," *Publications, Astronomical Society of the Pacific*, vol. 6, No. 35, 1894, pp. 104–112.
6. G. de Vaucouleurs, *Physics of the planet Mars*, Faber and Faber, London, 1954, 365 pp.
7. A. Dollfus, "Polarization Studies of Planets," pp. 343–399 in *The Solar System*, vol. 3, *Planets and Satellites*, G. P. Kuiper and B. M. Middlehurst (eds.), University of Chicago Press, Chicago, 1961 (see p. 386).
8. A. E. Douglass, *Annals of Lowell Observatory*, vol. 1.
9. A. E. Douglass, "A Cloud-Like Spot on the Terminator of Mars," *Astrophysical Journal*, vol. 1, No. 2, Feb. 1895, pp. 127–130.
10. C. Flammarion, *La planète Mars*, Gauthier-Villars et Cie., Paris, 1909.
11. F. Gifford, "The Problem of the Martian Yellow Clouds," *Monthly Weather Review*, vol. 91, Nos. 10–12, Oct.–Dec. 1963, pp. 610–612.
12. F. Gifford, "The Surface-Temperature Climate of Mars," *Astrophysical Journal*, vol. 123, No. 1, Jan. 1956, pp. 154–161.
13. W. D. Heintz, "On the Martian Yellow Cloud in 1956," *The Observatory*, vol. 78, 1958, pp. 203–204.
14. S. L. Hess, "Some Aspects of the Meteorology of Mars," *Journal of Meteorology*, vol. 7, No. 1, Feb. 1950, pp. 1–13.
15. P. Lowell, *Drawings of Mars, 1905*, Lowell Observatory, 1906.
16. P. Lowell, *Mars and its Canals*, Macmillan Co., New York, 1911, 393 pp.
17. Y. Mintz, "The General Circulation of Planetary Atmospheres," pp. 107–146 in *The Atmospheres of Mars and Venus*, Report of the Space Science Board, National Academy of Sciences-National Research Council, Publication 944, Washington, 1961.
18. S. Miyamoto, "Meteorological Observations of Mars During the 1962–63 Opposition, and Observational Study on the General Circulation of Mars," *Contribution Nos. 124 and 125, Institute of Astrophysics and Kwasan Observatory*, University of Kyoto. (See also reference number 19 below.)
19. S. Miyamoto and Y. Nakai, "Meteorological Observations of Mars During 1960–61 Opposition," *Contribution No. 105, Institute of Astrophysics and Kwasan Observatory*, University of Kyoto, 1961, 49 pp.
20. Observatoires Jarry-Desloges, *Observations des Surface Planètaires*, vols. 1 to 10 (for the apparitions of 1907 to 1941), Gauthier-Villars et Cie., Paris, various dates, 1908 to 1946.
21. F. Pasquill, *Atmospheric Diffusion*, D. Van Nostrand, London, 1962, 297 pp.
22. E. Pettit and R. S. Richardson, "Observations of Mars Made at Mount Wilson in 1954," *Report of the International Mars Committee*, Lowell Observatory, 1955, 113 pp. (also in *Publications, Astronomical Society of the Pacific*, vol. 67, No. 395, Apr. 1955, pp. 62–73).
23. W. H. Pickering, Mars Reports, Nos. 1 to 44, *Popular Astronomy*, vols. 22–38, 1914–1930.
24. E. C. Slipher, *Mars, the Photographic Story*, Sky Publishing Co., Cambridge, Mass., 1962, 168 pp.

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